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Micromagnetic modeling of autoresonance oscillations in yttrium-iron garnet films

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Abstract. One of the main problems of magnonics is finding the ways of efficiently spin waves excitation in a magnet. This paper considers the method of nonlinear amplification by phase locking of amplitude of dynamic magnetization in yttrium-iron garnet film performed by micromagnetic modeling with MuMAX^3 software taking into account the real materials parameters. It is shown that the excited magnetization precession can be considered as a autoresonance phenomena. The intensity of the autoresonance in ferrimagnetic yttrium-iron garnet films has threshold dependence on the chirp rate of the exciting magnetic field.

1. Introduction

Currently, there are many various theoretical finite-difference and numerical methods for studying dynamic magnetic properties of complex magnet systems. The numerical calculations are widely used to solve actual problems of microwave electronics connected with the effective excitation, amplification and propagation of spin waves in magnetic materials in the Landau-Lifshitz formalism [1]. One of the most popular and powerful open-source software solving the space- and time-dependent the Landau-Lifshitz-Gilbert (LLG) equations in nano- to micro-sized ferromagnets by finite-difference discretization methods is a MuMAX^3[1,2]. Its high performance and low memory requirements allow large-scale simulations to be performed in limited time and on inexpensive hardware. Due to the large number of considered interaction terms and the versatile geometrical options the MuMAX^3 has been successfully applied to predict the excitation and propagation of spin waves in real magnetic materials, e.g. yttrium-aluminum-garnet (YIG) films, e.g. [3-5].

Earlier the authors [6] theoretically developed the method of the nonlinear autoresonance amplification of magnetic oscillations in YIG. Namely, there we proposed the method for controlling the soliton amplitude using the resonance effect of a weak alternating magnetic field [7]. It was shown that, if a soliton is captured by an external alternating field with the eigen magnetic resonance frequency at the initial moment of time, then the resonance of the soliton and spin waves will be kept by the system, even under slow changes in the frequency of an external field, provided that certain threshold conditions for the field amplitude are met. Since the amplitude of the soliton depends on its frequency, it can be controlled under the self-sustained resonance or autoresonance conditions by slowly varying the frequency of an external pump field [8]. Despite the fact that this effect has a nonlinear nature, the necessary amplitudes of the swap field lie substantially below the nonlinearity threshold for magnetic oscillations. Though the autoresonance effect, which constitutes the basis of this method, has been widely discussed in various fields of modern physics of nonlinear phenomena [9], there are neither numerical calculations nor direct experimental confirmation, by exception work [10] considering plasma oscillations. Moreover, the developed analytical theory [6-8] does not take into account a few important for experiments parameters, for example: the geometry of the sample and demagnetizing factors, dipole-dipole interaction, attenuation and so on.

This way the experimental confirmation of the theory of autoresonance excitation of magnetic oscillations in a magnet is of high of interest. However, to improve the efficiency of potential experiments one obviously needs to complete the numerical simulation first.

In this work we show that the micromagnetic simulation can be successfully applied for modeling the autoresonance phenomena in thin YIG films. The obtained results are of high importance for experimental approving the theory of the autoresonance and improving the efficiency of magnonic devices.

2. Methods of simulation

Micromagnetic modeling was performed using the MuMAX^3 software. The YIG thin film was chosen as a modeling object, since this is a well-studied material with well-known reference parameters and low attenuation of the spin subsystem. Thin films are currently the most promising materials for microwave electronics in view of their miniature size, planar design, and the possibility of manufacturing by integrated technology. The micromagnetic modeling was performed for thin film of rectangular size 1600(length)×1600 (width)×160 (thickness) nm^3. This model was split up into cell matrix with the unit cell as 25×25×10 nm^3. The matrix cell size was determined by the following conditions: firstly, the simulation result should be physically meaningful - it should correlate well with the known date for YIG films, secondly, the time of simulation should be short and possibly minimal. By increasing the number of cells and reducing their size, we are getting closer to analytical approximations but the calculation time is increased tremendously. And, vice versa, by reducing the number of cells and increasing their size, the calculation time is reduced, but the result of calculations significantly differs from analytical one due to the large discretization.
The interactions between the cells were calculated using the Landau – Lifshitz equation [11,12],

$$\frac{\partial M}{\partial t} = \gamma\left[H_{eff} \times M\right] + \frac{\alpha}{M_0}\left[M \times \frac{\partial M}{\partial t}\right] \tag{1}$$

where M is the magnetization vector, α is the attenuation parameter, H_{eff} is the effective magnetic field, $\gamma = 1.74 \times 10^6$ Hz/Oe is the gyromagnetic ratio. The following material parameters of the YIG film were chosen for simulations: $M_s = 139261\cdot10^5$ A/m for saturation magnetization, $A_{ex} = 3.17 \times 10^{-12}$ J/m for exchange coupling [13].

The mesh size in the lateral direction was selected to satisfy the condition for spin waves existence in thin films - the cell size in the direction of applying an external constant magnetic field should be smaller than the exchange length in YIG [14]. The selected film thickness d = 160 nm meets this requirement with a tenfold excess of the magnitude of the magnetic length $l = \left(\frac{A_{ex}}{k_u}\right)^{\frac{1}{2}}$ = 13.5 nm. The dipole-dipole interactions were ignored at this stage due to the predominant contribution of exchange interactions for nanosize YIG films. Moreover such simplification sufficiently speeds-up the simulation.

Possible contribution of magnetocrystalline anisotropy in the YIG film was not taken into account due to its smallness [15]. At the same time, a perpendicular uniaxial anisotropy $k_u = 13.155\cdot10^3$ J/m^3 was introduced in the model of YIG film to make it easier to compare the simulation results with [8]. To freeze the spins in the (001) direction at the surface layers of the YIG film, the surface anisotropy constant value $k_s = 5k_u$ was also introduced. During the simulation the sample was completely magnetized by permanent external magnetic field H_z = 2 kOe directed along the easy magnetization axis (001).

3. Results and discussion

To determine the spectrum of magnetic eigen oscillations in the YIG film, a weak alternating exiting field H_x was applied in the film plane in (100) direction as a function:

$$H_x = h_0 \frac{\sin(f_0(t-t_0))}{f_0(t-t_0)}, \tag{2}$$

where h_0 is an amplitude of alternating exiting field (h_0 = 1 Oe), f_0 is the upper limit of exiting frequency (f_0 = 40 GHz), t_0 characterizes the simulation time (t_0 = 0.1 ns). The Fourier spectrum of the function (2) has a constant oscillation amplitude in the frequency range of interest (0.5-40 GHz) and sharply drops to zero outside it (Figure 1).

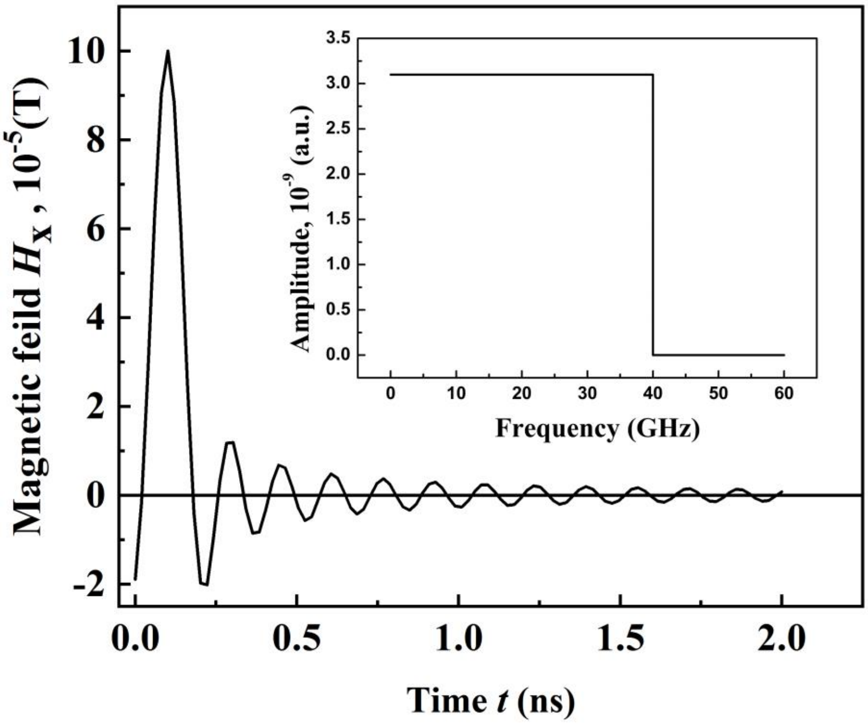

Figure 1. The pulse shape of the external magnetic field H_x along the (001) axis of the YIG film used for excitation of magnetic oscillations in the sample. The inset shows the Fourier transform of the equation (2).

At the first step, the magnetic oscillations in the YIG film exited by the H_x have been simulated in 100 ns timescale. Fast Fourier Transformation was used to analyze the simulated data and the spectrum of magnetic oscillation. The four various modes were obtained. Aiming to characterize it we studied the distribution of dynamic magnetization over the film thickness. First mode corresponds to the spin-wave resonance (SWR) with frequency ω_0 = 10.8 GHz (Figure 2). It is formed by standing waves with harmonic distribution and with nodes on sample surfaces. Second mode at ω_1=14.4 GHz corresponds to second SWR with the kink harmonic distribution in the middle of the film, the third and fourth modes were not taken into consideration due to their smallness.

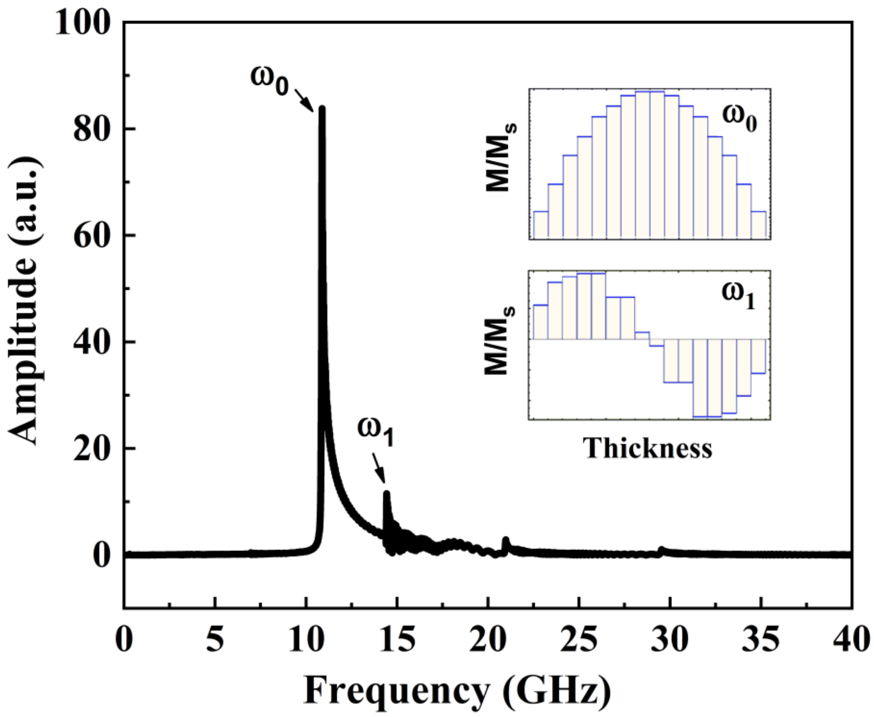

Figure 2. The spectrum of magnetic oscillations with four magnetization oscillation modes and distribution of dynamic magnetization over the sample thickness for ω_0 and ω_1 on the inset.

According to the theory [4] the autoresonance in YIG is characterized by an increase in the amplitude of magnetic oscillations at frequencies below the SWR. To excite the autoresonance it is necessary to reduce the frequency of exciting field. We start from the nearest SWR mode and then move to the low frequency area where there are no more intrinsic magnetic oscillations in the sample. Magnetic oscillations in the YIG film were excited by linear harmonic variables field h_0 with amplitude of 1 Oe directed in the plane of the film and perpendicular to the permanent field H_z. Exciting frequency ω was varied linearly according to the law:

$$\omega(t) \sim \omega_{start} + \frac{\varepsilon\,\beta^2\omega_0^2}{2}t \tag{3}$$

where ω_{start} – initial frequency above the first SWR (ω_{start} = 16 GHz), ω_0 – is the first SWR (10.8 GHz), $\beta = k_u/2M_s$ – is a normalized uniaxial anisotropy constant, ε – is proportionality constant, which characterizes the chirp rate $\varepsilon\beta^2$ ($\varepsilon \approx 10^{-6}$ rad^{-1}). The results of simulation are presented in the Figure 3. After defining the initial frequency parameters, it was necessary to determine the required non-dimensional chirp rate $\varepsilon\beta^2$ to get the autoresonance phenomena. During simulations, the average value of magnetization along the (001) axis over the entire thickness of the sample was maintained.

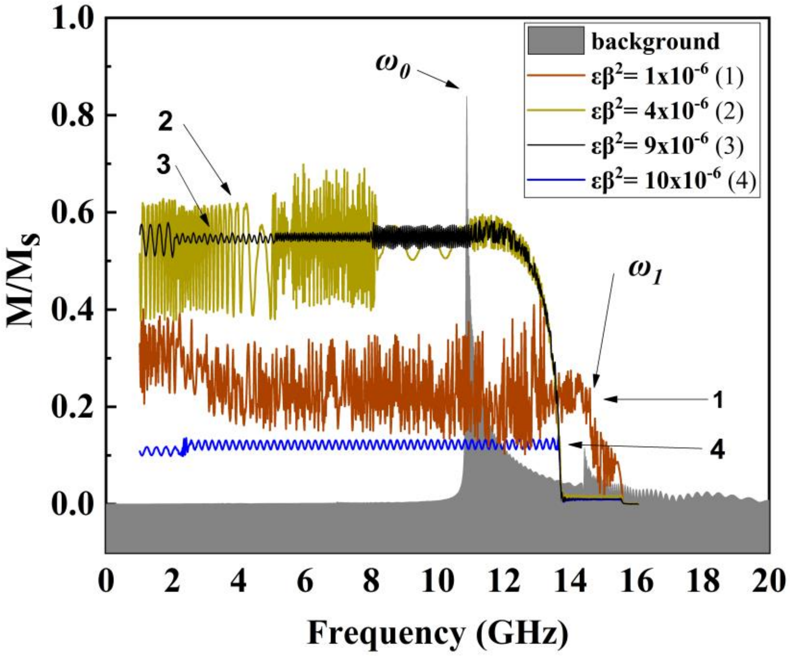

Figure 3. The simulated spectra of oscillations of relative magnetization along the (001) direction in the YIG film for different chirp rate $\varepsilon\beta^2$. Gray background: simulated spectrum of the eigen magnetic oscillations of the YIG film – first (ω_0) and second (ω_1) SWR modes.

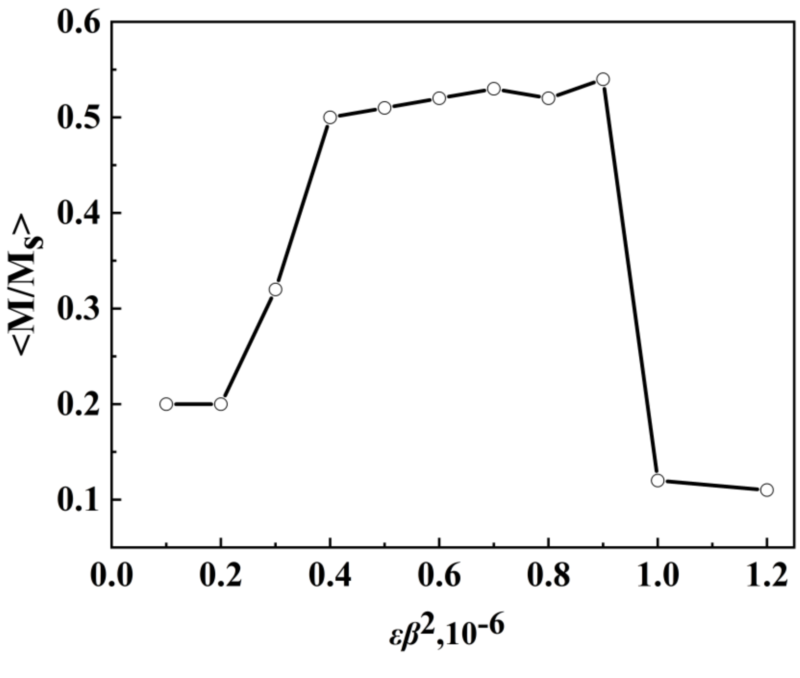

Figure 4. Threshold dependence of averaged value of relative magnetization $<M/M_s>$ from chirp rate $\varepsilon\beta^2$.

As it can be seen from the Figure 3, the rapid increase of the amplitude of relative magnetization oscillation occurs for some $\varepsilon\beta^2$. The modulation of M/M_s arises up to 60 % below 13.8 GHz. There is a threshold interval of $\varepsilon\beta^2$= from 4 to 9 × 10^{-6} over the film thickness (Figure 4). Taking into account the threshold character of the chirp rate at which a significant increase of magnetic oscillation occurs, stable high-amplitude magnetization oscillations in the region where there are no oscillations and small pump amplitude of the exciting field are observed, we believe that we have found the conditions for the occurrence of autoresonance to occur. The presence of rest dynamic magnetization at another chirp rates is possibly associated with neglecting Hilbert losses in our model.

With a further chirp rate decrease, we observe a strong beating and a decrease in the amplitude of magnetization oscillations, most likely due to the phase-out of intrinsic and exciting oscillations. The obtained results differ from the classical theory of autoresonance [3]. However, this problem is three-dimensional, for which there is no analytical solution.

4. Conclusion
The micromagnetic modeling in MuMAX^3 software was successfully applied for simulating the theoretically predicted autoresonance phenomena in the 160 nm yttrium-iron garnet film. It was approved that the crucial role in observing autoresonance phenomena is played by the speed of frequency changes – chirp rate of the exciting field. The effective autoresonance-like excitation of the dynamic magnetization (up to 60 %) was achieved in thin yttrium-iron garnet film in the permanent field 2 kOe with the amplitude of exciting magnetic field 1 Oe and the chirp rate about 525 MHz/sec in the wide spectral range 1-12 GHz. The results of work are promising for further successful experimental confirmation of the magnetostatic waves excitation by the autoresonance method.

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